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Cosmic Rays at Airplane Altitudes*

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A continuation of experiments made in a B-29 airplane to investigate the properties of cosmic rays is herein reported. Part I describes results on the latitude effect at 30,000 ft measured with counter telescopes and with both shielded and unshielded ionization chambers, from 64° geomagnetic north to the magnetic equator. A considerably larger latitude effect for the shielded ionization chamber than with the unshielded one or with counter telescopes indicates a definite change in the character of the radiation as one goes toward the equator at this altitude. The "knee" of the latitude effect is investigated in detail by a number of similar flights. Part II describes measurements made on density and formation of extended air showers. The apparatus was of such a nature as to be sensitive to relatively sparse showers. The densities obtained can be fitted to an integral power law spectrum with a negative exponent of 1.50 ± 0.05 for an altitude of 30,000 ft. Intensity-altitude curves are presented, showing that the development of smaller showers takes place nearer the top of the atmosphere than does the development of large showers. Derived zenith-angle dependencies at various altitudes are also given.

I. INTRODUCTION

DURING the summers of 1948 and 1949, a series of flights was made in a B-29 airplane in order to continue the studies of cosmic-ray intensities previously reported.[1] The purposes of these flights were to supplement those parts that required more detailed study. In particular (Part I), it was thought desirable (1) to check the latitude effects obtained with an unshielded Geiger tube telescope and ionization chamber, (2) to investigate further the latitude effect of an electroscope shielded by 11 cm of lead, and (3) to study the knee of the latitude curve in detail. Part II contains information on extended shower densities and intensities.

II. FLIGHT SCHEDULE

Two series of flights were made; one during the summer of 1948, and the other during the summer of 1949. The 1948 flights were all local flights from Inyokern, California, along the 117° W meridian, and were made for the purpose of investigating the "knee" of the latitude curve. The 1949 flights consisted of a trip to the magnetic equator, in Peru, and then up to the Great Slave Lake region in Canada. Table I gives the schedule of the individual flights. In general, the procedure during the individual flights was as previously described,[1] and only deviations from it will be mentioned.

III. DESCRIPTION OF APPARATUS

A. Equipment For Investigating the "Knee" of the Latitude Curve (Summer, 1948)

This equipment consisted of two unshielded telescopes of the type previously used,[1] and an unshielded ionization chamber. The telescopes were interleaved to conserve space, but were otherwise completely independent.

B. Equipment Used During the Summer of 1949

This equipment consisted of two unshielded telescopes, an unshielded and a shielded (11-cm lead) ionization chamber, and a shower array. In our previous experiments the equipment was converted from the former balloon-born apparatus.[2] Some difficulty was encountered with this type of battery-operated electronics and lightly constructed telescopes. For these reasons new equipment was constructed, similar to the old, but of a more rugged and permanent nature.

The unshielded ionization chamber was the same one used in former years, while the shielded ionization chamber consisted of an identical instrument incased completely inside a 11-cm lead shield.

C. Shower Density Equipment (Summer, 1949)

The shower measuring equipment consisted of six trays of Geiger tubes, similar to those used in the telescopes, so arranged that many physical spacings and coincidence arrangements could be used. Two quadruple coincidence channels were provided for, and coincidences between these two channels could be measured. The dispositions used are given in Fig. 1. The whole array was placed against the ceiling of the plane in order to minimize the effects of showers formed in the skin of the plane.

PART I. LATITUDE EFFECT

The measured latitude effect, both with unshielded ionization chamber and vertical counter telescope, was very close to the same as that measured during a similar flight made in 1948.[1] In fact, in each case the agreement in the measured values of the latitude effect was within 0.5 percent of being the same for the two series of flights. This agreement means that at the altitude at which these experiments were made (310 g cm^{-2}) the relative intensity of the primary radiation which could

* Supported in part by the joint program of the ONR and AEC.
[1] Biehl, Neher, and Roesch, Phys. Rev. 76, 914 (1949).
[2] Biehl, Montgomery, Neher, Pickering, and Roesch, Revs. Modern Phys. 20, 353 (1948).

TABLE I. Flight record.

Flight number	Date	Starting time	Finishing time	From	To
1-B-48	July 20, 1948	1300 GCT	2100 GCT	Inyokern	Inyokern
2	July 26	1700	2200	Inyokern	Inyokern
3	July 28	1600	2200	Inyokern	Inyokern
4	August 11	1700	2300	Inyokern	Inyokern
5	August 12	1700	2300	Inyokern	Inyokern
6	August 17	1800	2200	Inyokern	Seattle
7	September 23	2000	2300	Inyokern	Inyokern
8	October 21	1700	2400	Inyokern	Inyokern
1-B-49	August 1, 1949	1600	2400	Inyokern	Tampa
2	August 5	1500	2100	Tampa	Panama
3	August 6	1200	1800	Panama	Lima
4	August 9	1500	2200	Lima	Lima
5	August 13	1300	2100	Lima	Lima
6	August 16	1500	1800	Lima	Lima
7	September 20	1500	2100	Lima	Panama
8	September 21	1200	1900	Panama	San Antonio
9	September 21	0000	0400	San Antonio	Inyokern
10	October 27	2000	0200	Inyokern	Great Falls
11	October 29	1100	1900	Great Falls	Great Falls
12	October 31	2100	0600	Great Falls	Inyokern

penetrate to this depth at 51° N and at the equator was the same in August of 1949 as in June of 1948. These flights covered a range of latitude from 64° N to the geomagnetic equator in Peru.

However, the latitude effect with the shielded ionization chamber was found to be considerably larger than without the shield. As shown in Fig. 2, the ionization inside the 11-cm lead shield dropped from a value of 30.5 ions cm^{-3} sec^{-1} atmos^{-1} of air at geomagnetic latitude 51° N to 16.2 at the geomagnetic equator. The unshielded ion chamber gave a decrease of 36.1 percent between these two latitudes compared with the above value of 47 percent for that shielded with 11 cm of lead.

The larger latitude effect for the shielded ion chamber may be explained by a change in the character of the radiation at this altitude as one goes toward the equator. From the work of Simpson, Uretz,[3] and others, it is known that the latitude effect in nuclear events is much larger at this altitude than in the total radiation. Such events will undoubtedly be enhanced by the presence of the 11-cm lead shield.

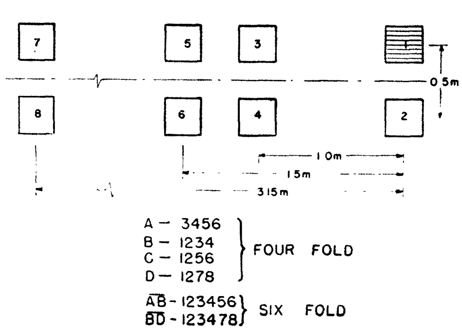

FIG. 1. Disposition of shower array. Each tray of Geiger counters contains eight counters connected in parallel. Coincidence arrangements are as indicated.

[3] J. A. Simpson and R. B. Uretz, Phys. Rev. **76**, 569 (1949).

The summer flights of 1948 were made under as nearly identical conditions as possible along the 117° W meridian, between the borders of Mexico and Canada. This was done in order to compare the latitude effect and the relative intensities obtained on successive days. Figures 3 and 4 show the data obtained for the average of the two counter telescopes over ten-minute periods and for the ion chamber. It should be noted that all flights except No. 5 were made at 33,000 ft,—No. 5 having been made at 30,500 ft.

An examination of the data plotted in Figs. 3 and 4 indicates that there is considerable choice as to the manner in which the curves may be drawn through the experimental points. The curves as shown are merely what appears to the authors to be a good fit, but are not necessarily completely justified by the experimental points. For example, flight 1 of Fig. 3 appears to have two plateaus between about 36° to 40°, and 42° to 48°, and possibly a third below 34° geographic latitude. It is interesting to note the correspondence of this particular telescope data with that of the electroscope taken on this same flight. Again, two plateaus are indicated, but the knees do not occur at the same latitude.

In general, it appears that there is fair agreement between corresponding telescope and electroscope data for each of the flights made on the same day (note points going north, and also going south). This is well illustrated by flight 4, where both methods of intensity measurements yielded values considerably below the average of the other flights. However, the lack of agreement between flights made on different days is too great to be experimental.

Such fluctuations have been reported previously,[4] particularly in connection with balloon flights. They are interpreted as being caused by variations in the primary radiation, and are more pronounced at the higher altitudes.

PART II. WIDE SHOWERS

By the investigation of extensive air showers at B-29 altitudes, it was hoped to gain information which will lead to a better understanding of these complex phenomena. In particular, in this set of experiments an attempt was made to investigate three effects:

A. The shower density as a function of spread of counters at certain fixed altitudes;

B. The development of showers of different size as measured by the altitude effect;

C. The latitude effect for extensive showers.

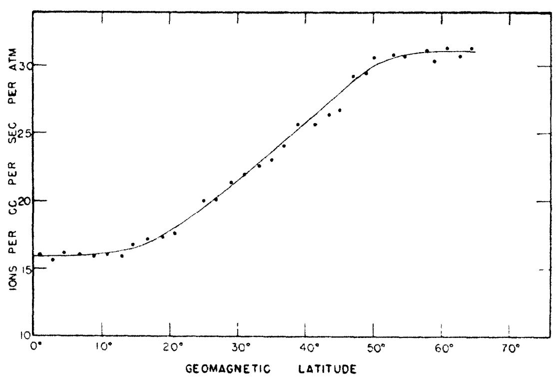

FIG. 2. Latitude effect obtained with an ionization chamber shielded with 11 cm of lead. Points are from both north and south-bound flights averaged over each two degrees of latitude. No comparable data were taken on the June, 1948, series of flights.

A. Shower Density

As pointed out by Cocconi *et al.*,[5] there are two simple methods of measuring shower density by means of coincidence counter arrangements. One (method I) is to compare the coincidence counting rates between various numbers of trays having the same total geometrical spread. In our case, fourfold to sixfold coincidence ratios were used. The other (method II) is to change the sensitive counter area of each tray of counters and compare the counting rates. In using this latter method, the number of counters per tray was reduced from the normal eight to four, by removing counters 2, 4, 5, and 7, as numbered from either side of the tray. To a first approximation this would reduce the sensitive area of each tray by a factor of one-half. However, owing to the zenith-angle dependence of the intensity of air showers,

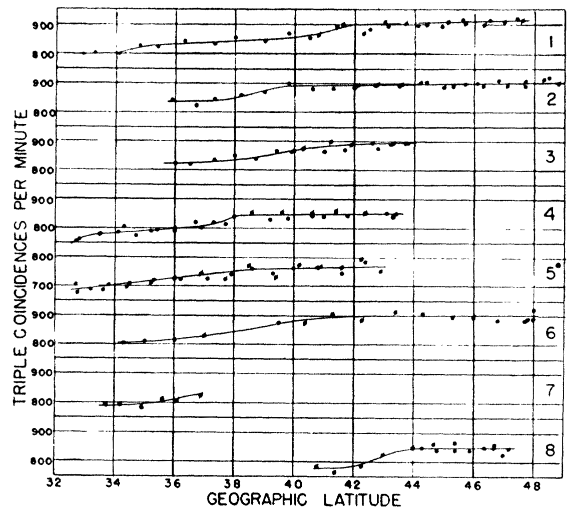

FIG. 3. The counting rates of the average of the two cosmic-ray telescopes are plotted as a function of geographic latitude for ten-minute intervals. All flights were made along the 117° W longitude. Note that flight 5 was made at an altitude of 30,500 ft, and all others at 33,000 ft. Crossed solid circles are going north, solid circles going south. To change from geographic to geomagnetic latitude at this longitude, add approximately seven degrees.

a shading effect takes place so that the effective ratio of areas is closer to 0.6. The methods of approximating this ratio will be treated in more detail later.

Table II gives a tabulation of the counting rates in counts-per-minute taken on each of the flights while the plane was maintained at a constant altitude. The probable errors for each rate and an average of the rates for similar flights are given. Care must be used in comparing counting rates, as in most cases they are not statistically independent. A first inspection shows that as the array is spread further out along the length of the plane, a decrease of about 5 percent per meter occurs in the counting rate. This fact allows an extrapolation to be

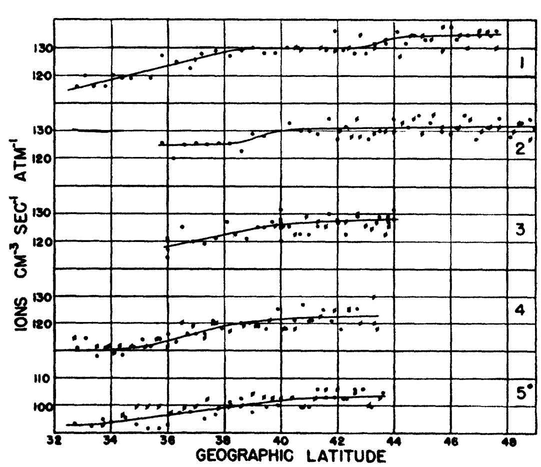

FIG. 4. The ionization as a function of geographic latitude is plotted for five-minute intervals, as obtained by an unshielded ionization chamber. Crossed solid circles are going north, solid circles are going south.

[4] Millikan, Neher, and Pickering, Phys. Rev. **66**, 295 (1944). See also: Biehl, Montgomery, Neher, Pickering, and Roesch, Revs. Modern Phys. **20**, 360 (1948).

[5] Cocconi, Loverdo, and Tongiorgi, Phys. Rev. **70**, 841 (1946).

TABLE II. Shower data.

		Rates (counts/minute)					
		4 fold				6 fold	
Flight	Notes	A $\frac{1}{2}$ m	B 1 m	C $1\frac{1}{2}$ m	D 3.15 m	AB $1\frac{1}{2}$ m	BD 3.15 m
2		5.09±0.11	4.79±0.10	...	...	2.92±0.08	...
3		5.25±0.10	4.94±0.10	...	...	3.02±0.08	...
7	8 counters	5.26±0.11	4.92±0.10	...	...	3.04±0.08	...
8	at 30,000′	5.31±0.09	4.92±0.09	...	...	3.02±0.07	...
10		...	5.04±0.10	4.87±0.10	...	2.92±0.08	...
11		...	4.91±0.08	...	4.64±0.08	...	2.85±0.07
	Average	5.24±0.05	4.89±0.08	4.87±0.10	4.64±0.08	2.986±0.035	2.85±0.07
4	4 counters	2.32±0.06	2.25±0.06	...	...	1.58±0.05	...
12	at 30,000′	2.17±0.05	2.12±0.05	...	...	1.28±0.04	...
	Average	2.23±0.04	2.18±0.04	...	...	1.405±0.03	...
5	8 counters	5.64±0.09	5.20±0.09	...	...	3.10±0.07	...
9	at 22,700′	5.24±0.10	4.84±0.10	...	...	3.01±0.08	...
	Average	5.47±0.07	5.02±0.07	...	...	3.07±0.05	...
5	8 counters at 35,000′	5.47±0.07	5.02±0.07			3.07±0.05	

made so that one may estimate with a fair degree of accuracy the counting rates of those arrays that time or facilities did not permit to be measured directly.

Figure 5 gives the altitude-dependence curve of extended air showers obtained from data taken on flights 2, 3, 5, 6, 7, 8, 9. Those points shown at 22,500 ft; 30,000 ft, and 25,000 ft were computed from the data taken while the plane maintained constant altitude by taking a weighted average of all data obtained for each array on each flight. The intermediate points were obtained by a similar averaging process from data taken while climbing to altitude. It is realized that such an averaging process is not strictly justified in that the altitude curves may differ in shape for different size arrays; however, the reduction in the scatter of the points obtained by this use of all available comparable data allows a good comparison to be made with existing altitude curves. On the same plot, are our data of June, 1948, and those of Kraybill[6] normalized at 6 meters of water.

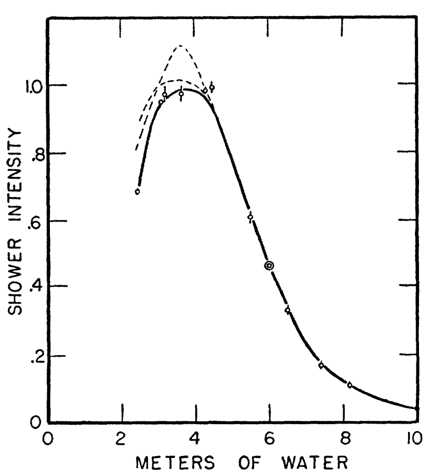

FIG. 5. The average shower intensity of all size arrays is shown as a function of atmospheric depth. For the purpose of comparison, our data of June, 1948 (higher dotted curve), and that of Kraybill (lower dotted curve) are also shown. Normalization has been made at six meters of water. Counting rates are in terms of the rate at the maximum of the curve.

In order to find the ratio of counting rates of 4 to 8 counters per tray, one must know the zenith-angle dependence of these extended showers. If one makes some modification of the usual assumptions[7] necessary to apply the generalized Gross transformation, it is possible to obtain the directional intensity of extended air showers.[8] These assumptions are (1) that the array may be represented by a horizontal flat surface, and (2) that the lateral spread of shower particles at a given depth is inversely proportional to the air density. Both of these assumptions are known to be in error, but it is believed the total error introduced into the final results will be small. Under these assumptions, together with an integral power law spectrum of $k\Delta^{-\delta}$, it can be shown that such a Gross transformation leads to a directional intensity at the vertical given by

$$N_0(h, N) = \tfrac{1}{2}\pi[(3\delta - 1)N - h(dN/dh)],$$

where h is the atmospheric depth, and N the counting rate of the shower array. By this means Fig. 6 is obtained from Fig. 5 where we have used a value of $\delta = 1.5$. Since the corrections needed to find the ratio of counting rates of 4 to 8 counters per tray are small, the value of δ need not be known accurately for this purpose.

[6] H. L. Kraybill, Phys. Rev. **76**, 1093 (1949).
[7] See L. Janossy, *Cosmic Rays* (Clarendon Press, Oxford, 1948), p. 139.
[8] H. L. Kraybill, Phys. Rev. **77**, 410 (1950).

If we again use the foregoing assumption (2), it is possible to find the zenith-angle dependence for a fixed altitude. We then find that

$$N_0(h, \theta) = N_0(h/\cos\theta, N)[\cos\theta]^{2\delta-2}.$$

These assumptions yield the zenith-angle curves given in Fig. 7 for 35,000 ft, 30,000 ft, and 22,500 ft. As pointed out previously, it is necessary to know the zenith-angle dependence in order to compute the ratio of the effective area of the 4 and 8 counter trays. This can now be done using numerical integration and the curves of Fig. 7. Actually, it was found to be easier to determine the ratio empirically. This was done by tracing the shadow of the trays cast by a distant light source and finding the mean area over azimuth angles for various zenith angles. Then, by multiplying this mean area by the zenith-angle curves and integrating, the following ratios were found for the effective areas of 4 and 8 counter trays: 22,500 ft, 0.564; 30,000 ft, 0.584; 35,000 ft, 0.641.

Cocconi,[5] as well as Kraybill,[6] has shown that if one assumes that the frequency of occurrence of showers whose density of particles is greater than Δ can be represented by a power law $K\Delta^{-\delta}$, where K is a constant and Δ is the particle density, then the counting rate of an n-fold array is given by

$$C(n, A) = \delta \int_0^\infty (1 - e^{-\Delta A})^n K \Delta^{-\delta-1} d\Delta,$$

where A is the effective area of each tray. It may readily be seen that method I is the case where A is held constant and n is varied (in this case the values of n are 4 and 6), and method II is the case where n is held constant and A varied. Table III gives the values of δ computed for these two methods.

The probable errors in the foregoing values of the exponent, δ, are estimated to be of the order of 0.05 by method I, and perhaps slightly higher by method II. Thus, it may be seen that a mean value of 1.50 ± 0.05 may be accepted for δ at 30,000 ft and 22,5000 ft, and 1.65 ± 0.05 for 35,000 ft. It is interesting to note how well methods I and II agree at 30,000 ft.

In attempting to compare this result with that of other experimenters, the difference in geometries must be borne in mind. This dependence on the experimental arrangement was first pointed out by Cocconi *et al.*,[5] and was shown to make comparison difficult. Nevertheless, they find a value of $\delta = 1.46$ near sea level, using counter areas comparable with ours. Kraybill,[6] with his apparatus under somewhat similar circumstances and altitude, finds a value of δ considerably higher (i.e., about 1.73). This difference is believed to be caused by the much larger relative areas used in this experiment, which gave counting rates about ten times as great as Kraybill's. This would make our apparatus more sensitive to the less dense showers.[9] This selectivity of showers with a certain density can perhaps be illustrated in another manner. In an earlier paper Kraybill[10] computes the average density of the showers detected in his apparatus to be $\frac{3}{4}$ particle per counter area (13 sq in.). A similar calculation for our apparatus

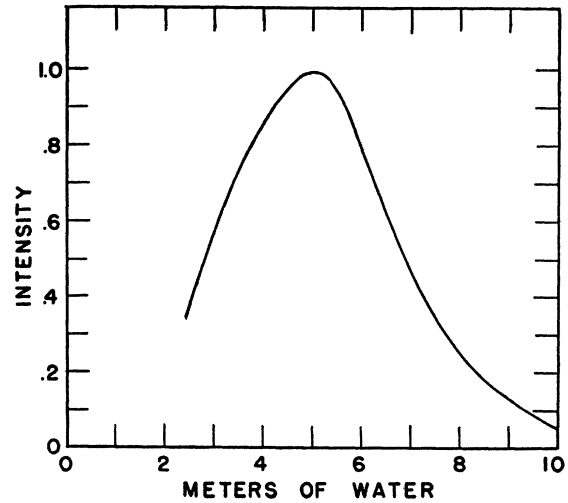

FIG. 6. Directional shower intensity at the vertical as a function of atmospheric depth, as obtained by a generalized Gross transformation of the curve given in Fig. 5.

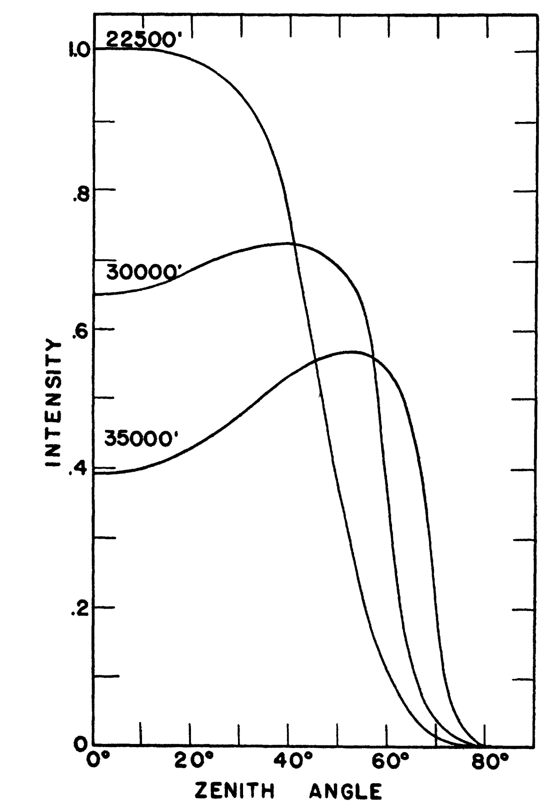

FIG. 7. Derived zenith-angle shower intensity curves for three different altitudes.

[9] See Fig. 6 of reference 5.

[10] H. L. Kraybill, Phys. Rev. 73, 632 (1948).

TABLE III. Computed values of δ.

Method	Altitude ft	Maximum spread in meters 0.50	1.00	1.50	3.16	Remarks
I	30,000	1.46	1.51	1.52	1.55	8 counters per tray
I	30,000	1.46	1.46	1.42	1.41	4 counters per tray
II	30,000	1.55	1.50	1.41		4 and 8 counters per tray
I	22,500	1.55	1.55	1.51		8 counters per tray
I	35,000	1.65	1.66	1.66		8 counters per tray

gives a value of 0.2 particle for the same area. Thus, it can be seen that Kraybill's showers had somewhat more than three times the average density of that detected by our apparatus.

The conclusion drawn from these data is that at airplane altitudes the frequency of occurrence of showers of certain densities may be represented by a power law whose exponent, δ, is close to that found at or near sea level. It is rather remarkable that this is so, since the showers at the higher altitude have not, in general, reached their maximum development, as they have at sea level.

Extensive showers are thought to be caused by primary particles with very high energy, which suffer nuclear collisions near the top of the atmosphere. In these interactions the major part of the energy of the primary appears to go into mesons, both charged and neutral. If it be assumed that a constant fraction of the initial energy, E, goes into neutral mesons, which soon decay to form gamma-rays, which in turn form cascade showers, then, according to shower theory, after the shower has developed one would expect the numbers, N, of shower particles to be proportional to the energy of the incoming primary. If these spread out over an area, A, the average density of the particles will be

$$\Delta = N/A = k'E/A. \tag{2}$$

Now, according to the data presented in the previous section, the frequency of occurence of showers of densities larger than Δ is $K\Delta^{-\delta} = K'E^{-\delta} = K'E^{-1.5}$.

A number of estimates from other cosmic-ray data have been made of the energy or momentum distribution of the primary particles. For the frequency of arrival of particles with energies larger than E, the estimates of n in E^{-n} vary from 1.5 at the lower energies to 1.9 for the highest.

Now, it is known from shower theory that the average energy of the secondary electrons is nearly independent of the energy of the primary. Furthermore, these extended showers must all start at about the same height in the atmosphere. It thus follows that if the shower arrives at all, the area covered by the shower will be nearly independent of the energy of the primary. It is

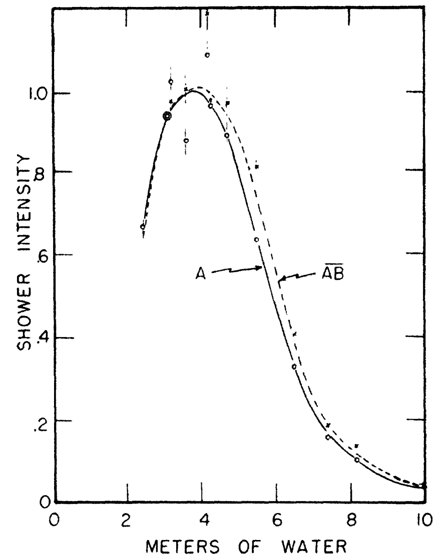

FIG. 8. Shower intensity as a function of atmospheric depth is shown for two different size arrays which have been normalized at 30,000 ft for comparison. Array A is four trays having a spread of one-half meter. Array AB is six trays having a spread of one and one-half meters. Notice the earlier development of the smaller array at high altitudes. The intensity is given in terms of the counting rate at the maximum of the curves.

to be expected then that the exponent of the density spectrum would be the same as that for the distribution in energy of the primary particles responsible for the showers. This appears to be approximately the case.

B. Shower Development

Figure 8 shows a comparison of the altitude effect obtained for a wide and a narrow array. Curve A is that obtained for an array of one-half meter spread. It is interesting to note the manner in which the narrower showers appear to develop nearer the top of the atmosphere than the wider showers. This behavior is to be expected on the basis of current shower theories.

C. Latitude Effect for Extensive Showers

A casual inspection of Table II is sufficient to show that no latitude effect was observed for even the smallest array used. This is in conformity with that found previously,[1] and is what one would expect if the primary particles causing the showers have momenta above 2×10^{10} Bev/c.

In conclusion, the authors wish to thank the Office of Naval Research and the United States Air Forces for making these flights possible. Particularly, we express our appreciation to the officers and men stationed at Inyokern, California. We also wish to thank Dr. R. F. Christy for his many helpful discussions.